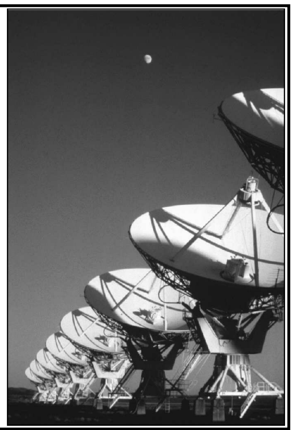
Mm-Wave Interferometry

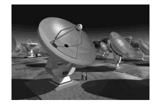
Debra Shepherd & Claire Chandler

- **Why a special lecture on mm interferometry?**
  - Everything about interferometry is more difficult at high frequencies
  - Some problems are unique at mm/sub-mm wavelengths & affect the way observations are carried out and data are reduced

Ninth Synthesis Imaging Summer School
Socorro, June 15-22, 2004



Outline



1. Science at mm & sub-mm wavelengths
2. Problems unique to mm/sub-mm observations
3. Solutions:
   - Correcting for atmospheric opacity
   - Absolute gain calibration
   - Tracking atmospheric phase fluctuations
   - Antenna and instrument constraints
4. Summary of existing and future mm/sub-mm arrays
5. Practical aspects of observing at high frequency with the VLA
6. Summary

Why do we care about mm/submm?

- Unique science can be done at mm/sub-mm wavelengths because of the sensitivity to thermal emission from dust and molecular lines
- Probe of cool gas and dust in:
  - Molecular clouds
  - Dust in dense regions
  - Star formation in our Galaxy
  - Proto-planetary disks
  - Star formation in the high-redshift universe

Science at mm/submm wavelengths: dust emission

In the Rayleigh-Jeans regime, $h\nu \ll kT$,

$$S_\nu = \frac{2kT\nu^2\tau_\nu\Omega}{c^2} \quad \mathrm{Wm^{-2}\,Hz^{-1}}$$

dust opacity, $\tau_\nu \propto \nu^2$

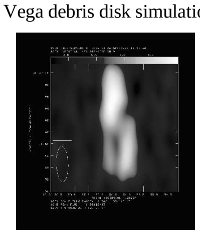
so for optically-thin emission, flux density

$$S_\nu \propto \nu^4; \quad T_B \propto \nu^2$$

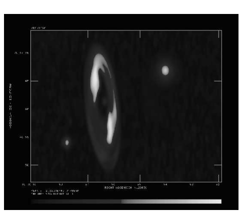
$\Rightarrow$ emission is brighter at higher frequencies

Dust emission in our Galaxy

Vega debris disk simulation: PdBI & ALMA



Simulated PdBI image

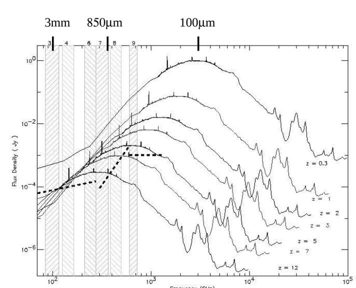


Simulated ALMA image

Star-forming galaxies in the early universe

As galaxies get redshifted into mm & sub-mm bands, dimming due to distance is offset by the brighter part of the spectrum being redshifted in.

Hence, galaxies remain at relatively similar brightness out to high distances.



(figure from A. Wootten)

Science at mm/sub-mm wavelengths: molecular line emission

7

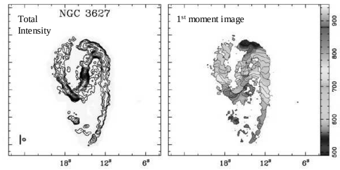
- Most of the dense ISM is H_2, but H_2 has no permanent dipole moment ⇒ use trace molecules
- Lines from heavy molecules → mm
- Lighter molecules (e.g. hydrides) → sub-mm

Table 28-1. Low Order Rotational Transitions of Simple Heavy Molecules

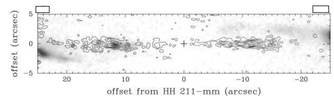
Molecule	J(1-0) GHz	J(2-1) GHz	J(3-2) GHz	n_{crit}[J(1-0)] cm^{-3}
CO	115.271	230.538	345.795	10^2 - 10^3
CS	48.991	97.981	146.969	10^3 - 10^4
HCN	88.631	177.260	265.886	10^5
HCO^+	89.188	178.375	267.557	10^5
SiO	43.122	86.243	130.268	10^3 - 10^4

8

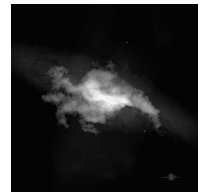
BIMA SONG ^{12}CO(J=1-0) mosaic (Helfer et al. 2003)



HH 211 molecular outflow (Chandler & Richer 2001)
VLA red- & blue-shifted SiO(J=1-0) with 2.12 μm H_2



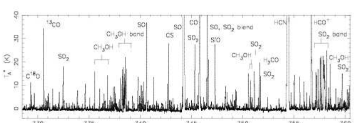
M82 starburst
Red: optical emission
Blue: x-ray emission
Green: OVRO ^{12}CO(J=1-0)
(Walter, Weiss, Scoville 2003)



9

Plus: many more complex molecules (e.g. N_2H^+, CH_3OH, CH_3CH_2CN, CH_2OHCHO, CH_3COOH, etc.)

- Probe kinematics, density, temperature
- Abundances, interstellar chemistry, etc…
- For an optically-thin line $S_\nu \propto \nu^4$; $T_B \propto \nu^2$ (cf. dust)



(Schilke et al. 1997)

Spectrum of molecular emission from Orion at 345 GHz

Problems unique to the mm/sub-mm

10

- Atmospheric opacity significant below 1cm: raises T_{sys}, attenuates source
  - Opacity varies with frequency and altitude
  - Gain calibration must correct for opacity variations
- Atmospheric phase fluctuations
  - Cause of the fluctuations: variable H_2O
  - Calibration schemes must compensate for induced loss of visibility amplitude (coherence) and spatial resolution (seeing)
- Antennas
  - Pointing accuracy measured as a fraction of the primary beam is more difficult to achieve: PB ~ 1.22 λ/D
  - Need more stringent requirements than at cm wavelengths for: surface accuracy & baseline determination
- Instrument stability
  - Must increase linearly with frequency (e.g. delay lines, oscillators, etc…)

Problems, continued…

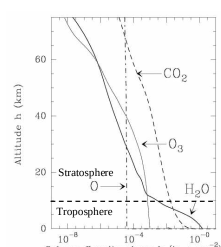
11

- Millimeter/sub-mm receivers (will not be discussed further)
  - SIS mixers needed to achieve low noise characteristics
  - Cryogenics cool receivers to a few K
  - IF bandwidth
- Correlators (will not be discussed further)
  - Need high speed (high bandwidth) for spectral lines: $\Delta V = 300$ km s^{-1} → 1.4 MHz @ 1.4 GHz, 230 MHz @ 230 GHz
  - Broad bandwidth also needed for sensitivity to thermal continuum and phase calibration, ≳ GHz
- Limitations of existing and future arrays
  - Small field of view, need for mosaicing: FWHM of 10 m antenna @ 230 GHz is ~ 30"
  - Limited *uv*-coverage, small number of elements (improved with CARMA, remedied with ALMA)

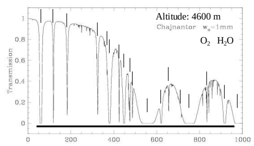
Atmospheric opacity

12

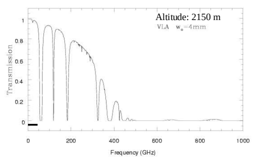
- Due to the troposphere (lowest layer of atmosphere): h < ~7-10 km
- Temperature decreases with altitude: clouds & convection can be significant
- Dry Constituents of the troposphere: N_2, O_2, Ar, CO_2, Ne, He, Kr, CH_4, H_2, N_2O
- H_2O: abundance is highly variable but is < 1% in mass, mostly in the form of water vapor
- Particulates (H_2O & dust)



Troposphere opacity increases with frequency: 13

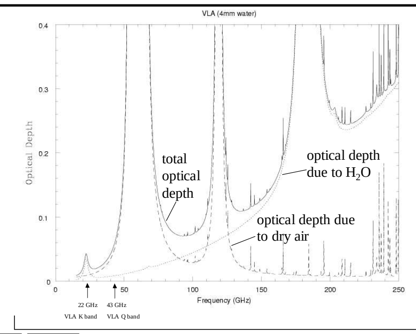


Models of atmospheric transmission from 0 to 1000 GHz for the ALMA site in Chile, and for the VLA site in New Mexico



⇒ Atmosphere transmission not a problem for λ > cm (most VLA bands)

Optical depth of the atmosphere at the VLA site 14



Effect of atmospheric noise on T_{sys} 15

- Consider a simple cascaded amplifier system, with one component:

input $S_{in}+N_1$ → Gain (gain G) → output = $G(S_{in}+N_1)$

Astro signal Noise

output noise relative to S_{in}, $N_{out} = G\,N_1/G = N_1$

N_1 includes contributions from sky, ground pickup by telescope side-lobes, electronics noise …

- Now consider two components:

input S_{in} → G1 (N_1) → G2 (N_2) → output = $G_2[G_1(S_{in}+N_1)+N_2]$

…divide by G_1G_2 to find noise relative to S_{in}, then

$$N_{in}^{eff} = N_1 + \frac{N_2}{G_1}$$

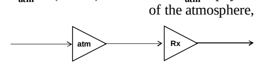
…and in general, $N_{in}^{eff} = N_1 + \frac{N_2}{G_1} + \frac{N_3}{G_1G_2} + \ldots$

➔ If first amplifier has high gain, then system noise is set by the first amplifier.

Atmospheric opacity, continued… 16

Now consider the troposphere as the first element of a cascaded amplifier system:

- $G_{atm} = e^{-\tau}$ (τ = atmospheric opacity; 'negative gain')
- $T_B^{atm} = T_{atm} \times (1 - e^{-\tau})$, where T_{atm} = physical temperature of the atmosphere, ~ 300 K



- "Effective" system noise temperature scaled to the top of the atmosphere (i.e., relative to the un-attenuated celestial signal) is:

$$T_{sys}^{eff} = e^{\tau} \times [T_{atm} \times (1-e^{-\tau}) + T_{rec}]^*$$

Atmospheric opacity · Emission from atmosphere · Receiver temperature

*ignoring spillover terms, etc.

Atmospheric opacity, continued… 17

- **Example: typical 1.3 mm conditions at OVRO**
  - Zenith opacity, $\tau_0 = 0.2$, at elevation = 30° ⇒ τ = 0.4
  - $T_{sys}(DSB) = e^{\tau}\,[T_{atm}(1-e^{-\tau}) + T_{rec}] = 1.5\,(100 + 50) = 225$ K
  - Dominated by the atmosphere (300 K)
  - If receiver is double side band and sideband gain ratios are unity, then

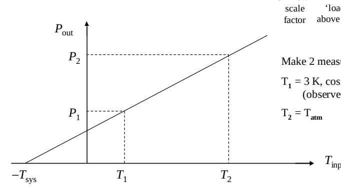
$T_{sys}(SSB) = 2\,T_{sys}(DSB) = 450$ K - *very noisy*

So: atmosphere is noisy and is often the dominant contribution to T_{sys}; it is a function of airmass and changes rapidly, so need to calibrate often.

Calibration of T_{sys} 18

- Systems are linear ⇒ output power, $P_{out} = m \times (T_{inp} + T_{sys})$
- If $P_{out} = 0$ then $T_{inp} = -T_{sys}$:

Unknown scale factor · Source 'load' above atm · Unknown system temp



Make 2 measurements of calibrated 'loads' T_{inp} :

T_1 = 3 K, cosmic microwave background (observe blank sky)

$T_2 = T_{atm}$

$$T_{sys} = \frac{(T_2-T_1)}{(P_2-P_1)} P_1 - T_1$$

Calibration of T_{sys}, continued…

- At cm wavelengths loads T_1 and T_2 are the 3 K cosmic background radiation and a noise source with known noise temperature switched into the signal path
- At mm wavelengths we need two known loads above the atmosphere!
  - (1) 3 K cosmic background radiation
  - (2) T_{atm} obtained from a load placed in front of the feed. If atmosphere is isothermal then $T_{ambient} \sim T_{atm}$:

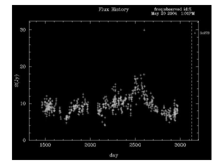
load $T_{amb} \rightarrow$ } atmosphere } $\rightarrow T_{amb}e^{-\tau} + T_{atm}(1-e^{-\tau}) = T_{atm}$

loss + emission

cancel for $T_{amb} = T_{atm}$

A few percent error is made by assuming isothermal atmosphere.
Once T_{atm} is known, you can calculate T_{sys}^{eff}, estimate τ and correct for it.

Absolute gain calibration



- There are no non-variable quasars in the mm/sub-mm for setting the absolute flux scale; instead, have to use:
- Planets: roughly black bodies of known size and temperature, e.g., Uranus @ 230 GHz has $S_\nu \sim 37$ Jy, diameter ~ 4″
  - If the planet is resolved by the array, have to use single-dish (total power) calibration
  - If the planet is resolved by the primary beam, have to know its side-lobe pattern
  - S_ν is derived from models, can be uncertain by ~ 10%
- Stars: black bodies of known size
  - e.g., Sun at 10 pc: $S_\nu \sim 1.3$ mJy @ 230 GHz, diameter ~ 1 mas
  - Problem: very faint! not possible for current arrays, useful for ALMA

Atmospheric phase fluctuations

- At mm wavelengths variable atmospheric propagation delays are due to tropospheric water vapor (ionosphere is important for $\nu < 1$ GHz)
- The phase change experienced by an electromagnetic wave is related to the refractive index of the air, *n*, and the distance traveled, *D*, by

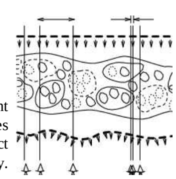
$$\phi_e = (2\pi/\lambda) \times n \times D$$

- For water vapor $n \propto \frac{w}{DT_{atm}}$ Where w = precipitable water vapor column

so $\phi_e \approx \frac{12.6\pi}{\lambda} \times w$ for $T_{atm} = 270$ K

Atmospheric phase fluctuations, continued…

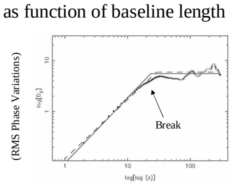
- Variations in the amount of precipitable water vapor therefore cause
  - Pointing offsets, both predictable and anomalous
  - Delay offsets
  - Phase fluctuations, which are worse at shorter wavelengths, and result in
    - Low coherence (loss of sensitivity)
    - Radio "seeing", typically 1-3″ at λ = 1 mm



Effect of structure in the water vapor content of the atmosphere on different scales. Patches of air with different water vapor content affect the incoming wave front differently.

Atmospheric phase fluctuations, continued…

Phase noise as function of baseline length



"Root phase structure function" (Butler & Desai 1999)

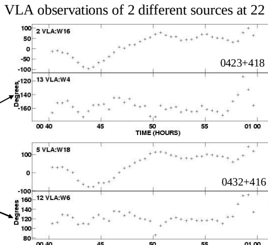
The position of the break and the maximum noise are weather dependent.
Kolmogorov turbulence theory $\rightarrow \phi_{rms} = K b^{\alpha} / \lambda$ [deg],

Where b = baseline length; α is a function of baseline length and depends on the width of the turbulent layer (1/3 – 5/6); λ = wavelength; and K = constant (~100 for ALMA, 300 for VLA)

Atmospheric phase fluctuations, continued…

Antenna-based phase solutions using a reference antenna within 200 m of W4 and W6, but 1000 m from W16 and W18:

VLA observations of 2 different sources at 22 GHz



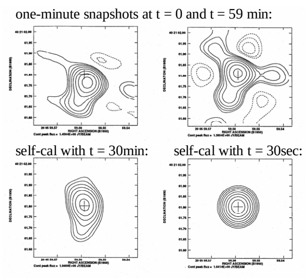
Antennas 13 & 12 are adjacent, phases track each other closely

Antennas 2 & 5 are adjacent, phases track each other closely

➔ Phase variations are tropospheric in origin, correlated on relevant timescales & baseline lengths

VLA observations of the calibrator 2007+404 at 22 GHz with a resolution of 0.1″:

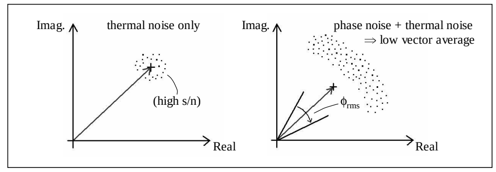
25



➔ Phase fluctuations with timescale ~ 30 s

Phase fluctuations: loss of coherence

26



Coherence = (vector average/true visibility) = $\langle V\rangle / V_0$

For a given measured visibility, $V = V_0 e^{i\phi}$

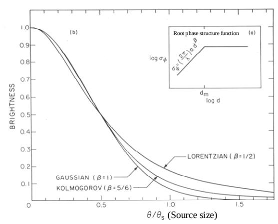
The effect of phase noise, ϕ_{rms}, on the measured visibility amplitude in a given averaging time:

$\langle V\rangle = V_0 \times \langle e^{i\phi}\rangle = V_0 \times e^{-\phi^2_{rms}/2}$ (assumes Gaussian phase fluctuations)

Example: if ϕ_{rms} = 1 radian (~60 deg), coherence = $\langle V\rangle / V_0$ = 0.60

Phase fluctuations: radio "seeing"

27



Phase variations leads to position variations (source is smeared out).

Point-source response function for various power-law models of the rms phase fluctuations, from Thompson, Moran, & Swenson (1986)

$\langle V\rangle = V_0 \times \exp(-\phi^2_{rms}/2) = V_0 \times \exp(-[K\, b^{\alpha} / \lambda]^2/2)$

- Measured visibility decreases with baseline length, *b*, (until break in root phase structure function)
- Source appears resolved, convolved with "seeing" function

Dependence of radio seeing on λ

28

- Consider observations at two frequencies, but the same resolution:

  λ_1, b_1

  $\lambda_2,\ b_2 = b_1(\lambda_2/\lambda_1)$ for the same resolution

then

$$\frac{(\phi_{rms})_1}{(\phi_{rms})_2} = \frac{b_1^{\alpha}/\lambda_1}{b_2^{\alpha}/\lambda_2} = \left(\frac{\lambda_2}{\lambda_1}\right)^{1-\alpha}$$

for example, $\alpha = 0.5$, λ_1 = 1 mm, λ_2 = 6 cm:

$$\frac{(\phi_{rms})_{1mm}}{(\phi_{rms})_{6cm}} \sim 8$$

⇒ Phase fluctuations severe at mm/submm wavelengths, correction methods are needed

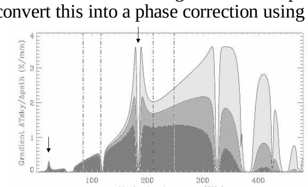
29

- Self-calibration: OK for bright sources that can be detected in a few seconds.
- Fast switching: used at the VLA for high frequencies and BIMA for ~1 km baselines. Choose fast switching cycle time, t_{cyc}, short enough to reduce ϕ_{rms} to an acceptable level. Calibrate in the normal way.
- Paired array calibration: divide array into two separate arrays, one for observing the source, and another for observing a nearby calibrator. Note:
  - Will not remove fluctuations caused by electronic phase noise
  - Only works for arrays with large numbers of antennas (e.g., VLA, ALMA)

Phase correction methods (continued):

30

- Radiometry: measure fluctuations in T_B^{atm} with a radiometer, use these to derive changes in water vapor column (*w*) and convert this into a phase correction using $\phi_e \approx \frac{12.6\pi}{\lambda} \times w$



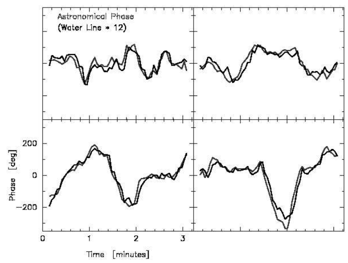
(Bremer et al. 1997)

Monitor: 22 GHz H_2O line (CARMA, VLA)

183 GHz H_2O line (CSO-JCMT, SMA, ALMA)

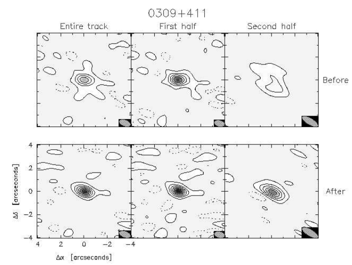
total power (IRAM, BIMA)

Examples of WVR phase correction: 22 GHz Water Line Monitor at OVRO



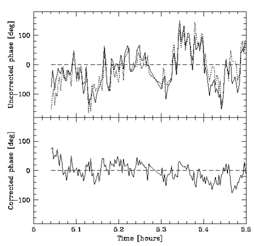
(Carpenter, Woody, & Scoville 1999)

Examples of WVR phase correction: 22 GHz Water Line Monitor at OVRO, continued…



"Before" and "after" images from Woody, Carpenter, & Scoville 2000

Examples of WVR phase correction: 183 GHz Water Vapor Monitor at the CSO-JCMT



Phase fluctuations are reduced from 60° to 26° rms (Wiedner et al. 2001).

Antenna requirements

- **Pointing:** for a 10 m antenna operating at 350 GHz the primary beam is ~ 18″
  - a 3″ error ⇒ Δ(Gain) at pointing center = 5%
  - Δ(Gain) at half power point = 22%
  - ⇒need pointing accurate to ~1″
- **Aperture efficiency, η:** Ruze formula gives
  - $\eta = \exp(-[4\pi\sigma_{rms}/\lambda]^2)$
  - ⇒for η = 50% at 350 GHz, need a surface accuracy, σ_{rms}, of 55μm
- **Baseline determination:** phase errors due to errors in the positions of the telescopes are given by

$$\Delta\phi = \frac{2\pi}{\lambda} \times \Delta b \times \Delta\theta$$

Δθ = angular separation between source & calibrator

Δ*b* = baseline error

Antenna requirements, continued…

Note: Δθ = angular separation between source and calibrator, can be > 20° in mm/sub-mm

⇒ to keep Δϕ < Δθ need Δ*b* < λ/2π

e.g., for λ = 1.3 mm need Δ*b* < 0.2 mm

Instrument stability

- Everything is more critical at shorter wavelengths.
  - Transmission line for the local oscillator should be stable to « λ
  - Needs to be temperature controlled
  - Round-trip path measurements can be ~ 1 turn/day, but quicker at sunrise/sunset
- ⇒ Calibrate instrumental phase every 20 to 30 mins

Summary of existing and future mm/sub-mm arrays

Telescope	altitude (feet)	diam. (m)	No. dishes	A (m^2)	ν_{max} (GHz)
BIMA[1]	3,500	6	10	280	250
OVRO[1]	4,000	10	6	470	250
CARMA[1]	7,300	3.5/6/10	23	800	250
NMA	2,000	10	6	470	250
IRAM PdB	8,000	15	6	1060	250
JCMT-CSO	14,000	10/15	2	260	650
SMA	14,000	6	8	230	850
ALMA[2]	16,400	12	64	7200	950

[1] BIMA+OVRO+Carlstrom 3.5 m Array at higher site = CARMA

[2] First early science expected in Q3 2007, planned for full operation by 2012

- Existing millimeter instruments are on sites at 1,000 to 2,400 m altitude, with typically a few millimeters of precipitable H_2O
- Primary beam (field of view) ~ 40″ (IRAM) to 120″ (BIMA) at 115 GHz, resolution 0.5″ to 2″.
- Note:
  - Small fields of view
  - Not sensitive to extended emission on scales > $\Omega_{PB}/3$
  - Mosaicing necessary for imaging even moderate-sized areas
  - Small number of antennas make it difficult to build up good *uv*-coverage ⇒ not many *independent* pixels in the image plane
- Hence the need for CARMA & ALMA

Practical aspects of observing at high frequencies with the VLA

Note: details may be found at
http://www.aoc.nrao.edu/vla/html/highfreq/

- Observing strategy: depends on the strength of your source
  - Strong (≥ 0.1 Jy on the longest baseline for continuum observations, stronger for spectral line): can apply self-calibration, use short integration times; no need for fast switching
  - Weak: external phase calibrator needed, use short integration times and fast switching, especially in A & B configurations
  - Sources with a strong maser feature within the IF bandpass: monitor the atmospheric phase fluctuations using the maser, and apply the derived phase corrections to a continuum channel or spectral line channels; use short integration times, calibrate the instrumental phase offsets between the IFs being used every 30 mins or so

Practical aspects, continued…

- Referenced pointing: pointing errors can be a significant fraction of a beam at 43 GHz
  - Point on a nearby source at 8 GHz every 45-60 mins, more often when the az/el is changing rapidly. Pointing sources should be compact with $F_{8GHz} \geq 0.5$ Jy
- Calibrators at 22 and 43 GHz
  - Phase calibration: the spatial structure of water vapor in the troposphere requires that you find a phase calibrator < 3° from your source, if at all possible; for phase calibrators weaker than 0.5 Jy you will need a separate, stronger source to track amplitude variations
  - Absolute Flux calibrators: 3C48/3C138/3C147/3C286. All are extended, but there are good models available for 22 and 43 GHz

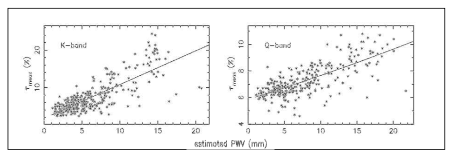
Practical aspects, continued…

- Opacity corrections and tipping scans
  - Can measure the total power detected as a function of elevation, which has contributions

$$T_{sys} = T_0 + T_{atm}(1 - e^{-\tau_0 a}) + T_{spill}(a)$$

and solve for τ_0.

  - Or, make use of the fact that there is a good correlation between the surface weather and τ_0 measured at the VLA (Butler 2002):

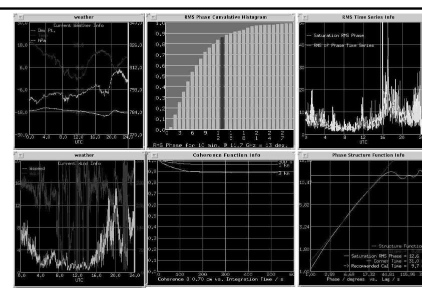


and apply this opacity correction using FILLM in AIPS

Practical aspects, continued…

- If you have to use fast switching
  - Quantify the effects of atmospheric phase fluctuations (both temporal and spatial) on the resolution and sensitivity of your observations by including measurements of a nearby point source with the same fast-switching settings: cycle time, distance to calibrator, strength of calibrator (weak/strong)
  - If you do not include such a "check source" the temporal (but not spatial) effects can be estimated by imaging your phase calibrator using a long averaging time in the calibration
- During the data reduction
  - Apply phase-only gain corrections first, to avoid de-correlation of amplitudes by the atmospheric phase fluctuations

The Atmospheric Phase Interferometer at the VLA



Accessible from http://www.vla.nrao.edu/astro/guides/api

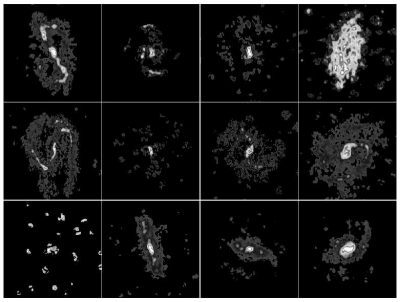
Summary

43

- Atmospheric emission can dominate the system temperature
  - Calibration of T_{sys} is different from that at cm wavelengths
- Tropospheric water vapor causes significant phase fluctuations
  - Need to calibrate more often than at cm wavelengths
  - Phase correction techniques are under development at all mm/sub-mm observatories around the world
  - Observing strategies should include measurements to quantify the effect of the phase fluctuations
- Instrumentation is more difficult at mm/sub-mm wavelengths
  - Observing strategies must include pointing measurements to avoid loss of sensitivity
  - Need to calibrate instrumental effects on timescales of 10s of mins, or more often when the temperature is changing rapidly

Rewards are ample!

44



BIMA Survey of Nearby Galaxies - SONG: (Helfer et al. 2002)